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INVESTIGATION OF TRANSFER STANDARDS IN THE HIGHEST RANGE UP TO 50 MN WITHIN EMRP PROJECT SIB 63

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Abstract – The EMRP SIB 63 project was established to give the end user the needed measurement technology, traceability and tools to work in the highest force range up to 50 MN. This paper describes work package WP1 which deals with BU systems as transfer standards. A knowledgebase was collected to optimize the design with complex studies and models. Within the project, also an uncertainty model and technical guidelines will be developed.

Keywords: transfer standard, meganewton, build-up system

1. INTRODUCTION

In recent years, there has been a change in the demand for measuring the highest forces. This is due to the boom in the regenerative energy sector and new developments in civil engineering. For forces larger than 16.5 MN, the traceability by European NMIs is limited to 30 MN with uncertainties of about 0.15 %, and above 30 MN no traceability is available in Europe. The increased demand by users for the highest nominal values of forces up to 30 MN cannot be covered by NMIs and for forces up to 50 MN there is no traceability in Europe at present. The current approach is to extrapolate data based on calibrations in the lower range to higher values. Until now, there has been no way to quantify the risk associated with this procedure as there is a lack of knowledge on device behaviour in the high range (since calibration was not possible).

2. STRUCTURE OF THE EMRP PROJECT SIB 63

For these reasons, the EURAMET research project SIB 63 was established. The main objective is to give users new procedures and technical guidelines on the use of high force measurement devices. Methods of uncertainty calculation and improvements in the dissemination of force from primary standards to calibration services and testing laboratories will also be developed. The structure of the project is presented in Figure 1. The work of the project is split up into six work packages (WP) which contain four technical subprojects.

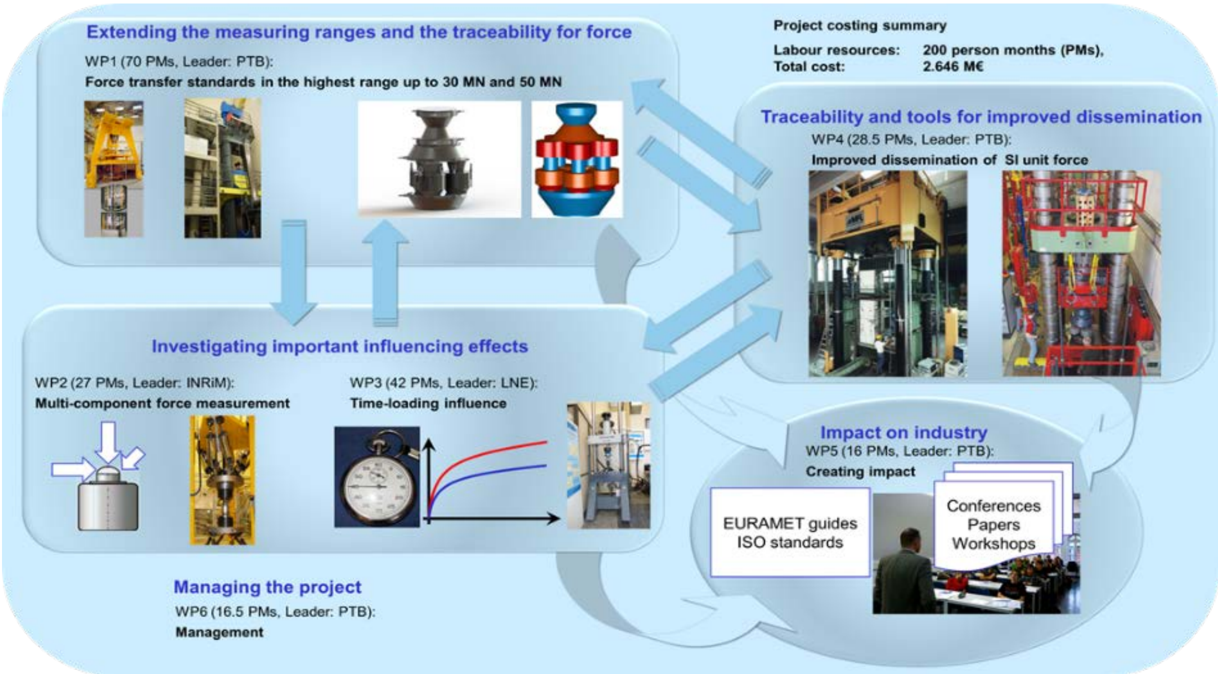

Fig. 1. Structure of the project divided in six work packages

Work package 1 deals with new transfer standards based on the principle of a build-up System (BU-System) or the extrapolation of data for forces in the meganewton range. As an example within this WP, PTB´s new 30/50 MN BU system (Figure 2 and 3) will be investigated and used to enable a future traceability up to 50 MN. Work package 2 will address the influences of parasitic components which are related to multi-component measurements. The determination of the influence of the time-loading procedure on industrial force measurements is part of WP3. Finally, WP4 will cover the preparation of guidelines and software tools to determine the uncertainties for whole measurement instruments which will be made available for calibration laboratories and the users of force transducers with industrial applications.

In addition, two administrative packages complete the whole project. Work package 5 will be the interface to the end users and it organizes project impact by outreach activities in the form of workshops and training courses with stakeholders, publications, promoting new guidelines and software tools and by providing input into relevant standardisation committees. Finally, work package 6 is dedicated to the management of the project.

3. DEVELOPMENT OF TRANSFER STANDARDS IN THE RANGE UP TO 50 MN

This paper deals with the basic structure and work done after half has been completed. It especially focuses on WP1. The main idea of this part of the project is to use BU systems for the extrapolation of force as it has made no economic sense up to now to decrease the highest national standards with the lowest uncertainties

Work package 1 itself is composed of six tasks. Ultimately, it aims to develop tools and work instructions about the use of BU systems or to extrapolate data in order to calibrate force calibration or testing facilities with force ranges higher than the biggest national force standards with acceptable low uncertainties.

Up to now, the knowledge about uncertainties using BU systems has been scarce and limited to special applications at NMIs under laboratory conditions.

To start the investigations which are meant to improve measurement procedures and mechanical design, a comprehensive knowledge base is important. For that reason, many BU systems have been investigated in the first Task 1.1 of the WP. It was the aim of this first task to get a broad knowledge base about as many BU systems as possible according to their behaviour comparing a single and a combined calibration.

Task 1.1 also includes the more precise investigation of BU systems with several partial range calibrations and the use of machines with the lowest uncertainties within the EMRP consortium.

It is also the aim of this task to investigate different types of transducers used in the BU systems, especially the two types which have been used most often, standard column type and bending ring type transducers. As a result, some assumptions made with the knowledge of smaller transducers in the kN range, will not apply in the MN range. In general, bending ring transducers show the best behaviour in the range up to 1 MN. But at higher forces, several particular kinematic effects might lower the constructional advantage of these transducers with a bigger shape. The mechanical quality of steel declines with the size of the manufactured components. Heat treatment of steel, for example, gets more and more difficult. The material quality, given by the material texture, becomes more and more inhomogeneous. In addition, the build-up systems grow much bigger when using any kind of more complex, in usual improved construction outlines of the transducers. With the growing size and a bigger ratio of the size of the compression plates of the machine and the overlap of the position of the transducers within the BU system, elastic deformations in the adaptation parts lead to higher uncertainties due to bending moments and cross forces. First results of the project clearly show that BU systems with no overlap of the system above the force introduction plates of the machines have an advantage. As an example, some NMIs in principle uses machines with very wide compression plates and BU systems with quite thin column type transducers. The ratio of the results gained from single transducers calibrations and combined calibration in a BU system is much smaller, in case of that NMI it is negligible for the traceability of their hydraulic machines with uncertainties of 0.1%.

As an example, the influence of cross forces and bending moments is demonstrated with the 30 MN BU system from PTB. The system is built of three 10 MN transducers and a set of appropriate adaptation parts. For 50 MN, two additional 10 MN transducers and enlarged adaptation parts will be used (Figure 2). Certainly, the use of the bigger plates even for the 30 MN system might be advantageous. This was tested with unexpectedly significant results. Figure 3 shows three of the transducers mounted in the bigger adaptation plates with much higher stiffness.

Fig. 2. Photo of five 10 MN transducers within the 50 MN BU system beside a numerical simulation of the area of the force introduction

The differences between a single and a combined calibration are shown in table 1. It strongly points out the disadvantage of the more flexible embodiment. However, such optimized stiff conditions are not always practicable in the environment of material testing facilities. Compression plates might have a limited size due to special requests for the application of the machine. Additionally, in the case of PTB´s 30 MN system, it is difficult to handle the 50 MN plates as they have a weight of 900 kg each.

Fig. 3. Three 10 MN transducers mounted with the adaptation parts for five transducers to achieve a higher stiffness in comparison with the smaller parts of the 30 MN system (Fig. 2)

Table 1. Deviation between the use of different adaptation plates as shown in Fig. 2 and Fig. 3

Force F_{LS}	Relative deviation between single and combined use of the transducers in %	
kN	30 MN plates	50 MN plates
1500	0.13	-0.02
3000	0.15	0.00
4500	0.15	0.00
6000	0.15	0.01
7500	0.15	0.01
9000	0.15	0.01
10500	0.15	0.01
12000	0.15	0.01
13500	0.14	0.01
15000	0.14	0.01
16500	0.14	0.01

But finally, it is not our requirement to improve only the stiffness. The deviation between a single and a combined calibration as a systematic error can be corrected in the uncertainty model. Up to now, such a model has not been developed. This work is one basic part of WP1, especially of its Task 1.3.

Before defining such a correction factor, it is certainly the first step to optimize the design of BU systems to keep this correction with its associated uncertainty as small as possible. This constructive work will be done in Task 1.2. The knowledge base of Task 1.1 will be used in addition to numerical simulations and the comparison to scaled models in order to develop an optimized design. The scaled models of possible solutions for this design will be tested in a smaller force standard machine (100 kN FSM at PTB) with lowest uncertainties so that the results of the optimization can be experimentally verified within this task. The benefit using scaled models is the possibility to quickly change and analyse different force introduction layouts.

The aim of this analysis process is to identify parameters which allows the generation of parasitic forces to be reduced. As an example, one solution is to build an upper loading plate with a special ‘bell-like’ shape which will not generate substantial cross forces nor bending moments due to its elastic behaviour.

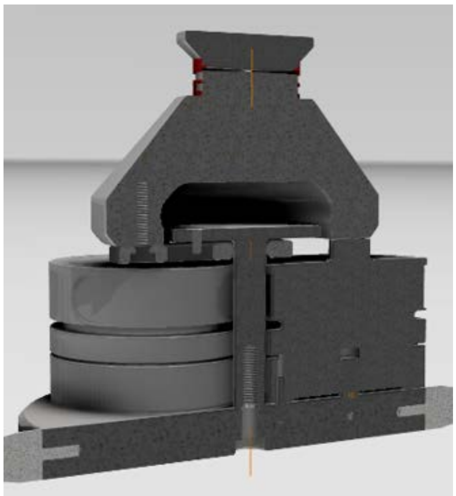

Fig. 4. A cut of the 3 x 10 kN BU System equipped with a new shape of the pressure plate as well as the transport lock

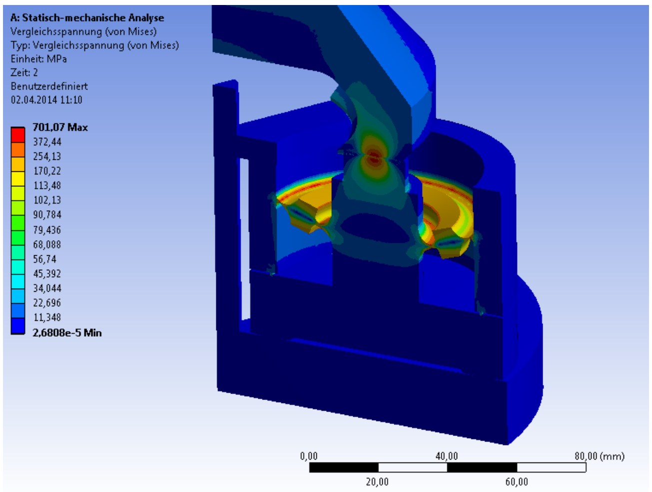

Fig. 5. Numerical analysis results of the deformation behaviour with special regard to the generation of parasitic forces

One scaled model has been purchased from the manufacturer of its ‘big brother’, HBM Darmstadt, shown in Figure 4. This small BU System mechanically compares to the two big ones, 3 x 1 MN and 3 x 2 MN and is the first one which will be investigated.

Different types of usual force introduction patterns have also been built and tested in different sizes and small models of BU systems to gain experience about the influence of the size and the significance of such models. First results show that it is difficult to compare the behaviour between different sizes of the same BU system type. However, these models can easily be used to determine the influence of shape and size of the adaptation parts and compression plates.

Fig. 6. 3 × 20 kN, 3 × 1 MN and 3 × 2 MN BUS system of same type

4. SIGNAL GENERATION AND CALCULATION ABOUT UNCERTAINIES

Task 1.3 contains the development of an uncertainty model and a technical guide for the calibrations. Up to now, the use of BU systems has not been specified in any normative way. When the project started, no agreed linguistic usage and detailed information about the use and analysis of the measurement results of BU systems were defined. As an example, it was a widespread misunderstanding that the signal of a sum box and the average of the single measured signals of the transducers were the same. The BU system dictionary and a dedicated evaluation method for the analysis of BU systems will be presented in an additional paper, as this work is too complex to be placed within this work. A short extract of the dictionary is presented in Table 2 as it is necessary as a definition for the following theory for an uncertainty model for BU systems.

In general, the calculation of the additional uncertainties for a BU system will include the determination of the uncertainties for the extrapolation of reproducibility, repeatability, creep and interpolation error.

Former works [1] describe such an expanded model as an expanded, updated collection of uncertainty components of an uncertainty model for a usual single transducer. Figure 7 describes the principle of the signal generation from the real acting force to the measured sum force.

Table 2. Designations of quantities related to BU system investigations

SYMBOL / UNIT [SOURCE]	(SHORT) ENGLISH DESIGNATION
F_R / N	real acting force
F_I / N [ISO 7500]	indicated machine force
F_{LS} / N	load step
F_{IS} / N	indicated single transducer force
F_{IB} / N	indicated build-up system force
F_S / N	sum force
F_{RS} / N	reference sum force
d_S	summation deviation
d_L	real single-indication deviation
d_I	indication deviation
d_K	connection deviation

From Figure 7 follows that F_S can be defined using equation (1):

$$F_S = F_1 + F_2 + F_3 + F_{korr}(d_L) \quad (1)$$

d_L is an important component for the uncertainty model. The sum F_S of the three components $F_{IS,i}$ is, however, not equal to the real acting force F_R generated by the force machine, which is for a force standard machine equal to the force step F_{LS}. This deviation between F_S and F_{LS} is called d_L.

Equation (1) can be used as the model function for the uncertainty model. This is suitable because all unknown uncertainties are combined in d_L and the uncertainties for the components $F_{IS,i}$ can easily be taken from the ISO 376 calibration and the uncertainty calculation according Annex C.1.

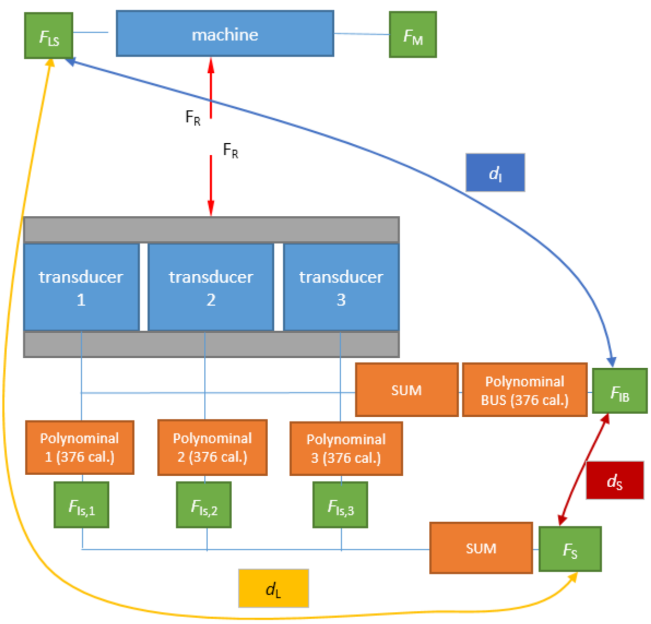

Fig. 7. Signal generation from real acting force to measured sum force

According to the GUM and [2], the uncertainty can be calculated as follows:

$$Y = f(X_1 + \ldots + X_N) - B \quad (2)$$

Y measurand with y estimation for the measurand

X_i input quantity with x_i measurand for the input quantity, each single x_i is defined by the measured force of a single transducer following the equation $F_{\mathrm{IS},i} = a_1 \cdot S_i + a_2 \cdot S_i^2 + a_3 \cdot S_i^3$

B systematic deviation, b is the estimated value which is defined in this model as d_{L}

Finally, the following function can be achieved following the calculations of uncertainties according to the GUM:

$$w_c(y) = \sqrt{(w(x_1))^2 + \ldots + (w(x_N))^2 + (w(b))^2} \quad (3)$$

In doing so, the uncertainties for the single transducers can easily be taken from the ISO 376 calibration result.

The next aim is to define the systematic deviation b and its uncertainty $w(b)$.

There is a broad variety of influences on this value. Ultimately it is the aim of this research project to find more and more components to describe this uncertainty. For a first model, the whole deviation between a single and a combined calibrations can be taken into account with b as a systematic uncertainty. Certainly the GUM demands that all known uncertainties shall be determined and corrected (section 3.24). In future, the uncertainty b will be corrected.

The uncertainty model, especially the estimation of b, should be adapted to practical use. The uncertainty model and the calibration procedure should first enable the calibration of a BU system to be used as a transfer standard and subsequently the calibration of a testing or calibration facility. Within a widespread range of different usages, the three usual cases will be discussed in the project. Depending on the availability of technical equipment, the following cases will be analysed:

1. The BU system can be investigated in a calibration facility with the lowest uncertainties up to the nominal load. The typical behaviour of the system can be analysed to describe precisely b.
2. The BU system can only be analysed in a force standard or calibration facility up to the nominal load of a single transducer. b will be analysed at its partial load, typical corresponding to one-third of the nominal load. For higher values, b must be safely estimated according to a knowledge base, compiled in a first draft within this project.
3. The previous cases require the availability of a simultaneous 3 channel amplifier. If this is not the case, a summary box must be used. Due to this, additional uncertainty components must be added, especially because the behaviour up to the nominal load cannot be analysed precisely for every single transducer.

The main question is, whether there is a repeatable possibility to investigate b until the nominal load. For this reason, some investigations will also be undertaken in several different machines at the EMRP partners.

Finally, even the uncertainties taken for the single transducer from the ISO 376 calibration will be discussed within the project. As an example, the rotational error of the single transducers of a BU system is always much bigger than the same error in the use as a BU system.

The aim of the subsequent tasks 1.4 and 1.5 will be to analyse PTB's new BU system which comprises a 30 MN and a 50 MN BUS. Within this task, all parameters that can be used to describe the particular behaviour of BU systems will be figured out and investigated to be able to calibrate testing and calibration facilities up to 30 MN and to perform an inter-laboratory comparison. The result of this task will be the capability to calibrate facilities according to ISO 7500-1 and to support the CMC-entry for FSMs in the highest range.

The first measurements using the 30 MN BU system have been performed at NPL London and at BAM Berlin. The deviation for d_{L} could be determined and is quite similar in all machines. However, the real indication deviation, d_{L}, found using the 30 MN BU system is larger than expected. The reason for this is the elastic deformation of the ground plate. Numerical computations show a generation of cross forces up to 350 kN for each transducer at 30 MN axial load to the entire system. To reduce this, an experiment has been carried out using a much bigger platen which has been designed for up to 50 MN. As already mentioned, the results are shown in Tab. 1. The transducers together with their housing will be overworked in future regarding several design parameters, i.e. their diameter as well as the bearing conditions. This will be done to reduce their sensitivity for parasitic forces generated by the loading plates. The concept for a load cup for the 30 MN system as shown in Figure 4 and 5 is planned to be realized within the next year.

Figure 4 shows a 6 MN BU system owned by PTB. This system is also used within the EMRP project. As mentioned, the uncertainty for d_{L} will be determined. First experiments show that this factor might depend on the machines used. To test this hypothesis, the 3 × 2 MN BU system will be used in several facilities by the project partners. Another important analysis is the determination of the force introduction point. By this there is a link to the work package 2. In this work package, a 5 MN hexapod has been designed and manufactured. It enables the measurement of axial forces up to 5 MN in addition to all three cross forces and bending moments. During measurements at the 9 MN FSM at INRIM in Torino, the 6 MN BU system of PTB has been mounted on top of the Hexapod and has been loaded up to 5 MN. In doing so, the system could be calibrated up to 5 MN using the BU System as a reference (Figure 8). In addition, all six load components of the Hexapod and the signals of the three single transducers have been measured and recorded.

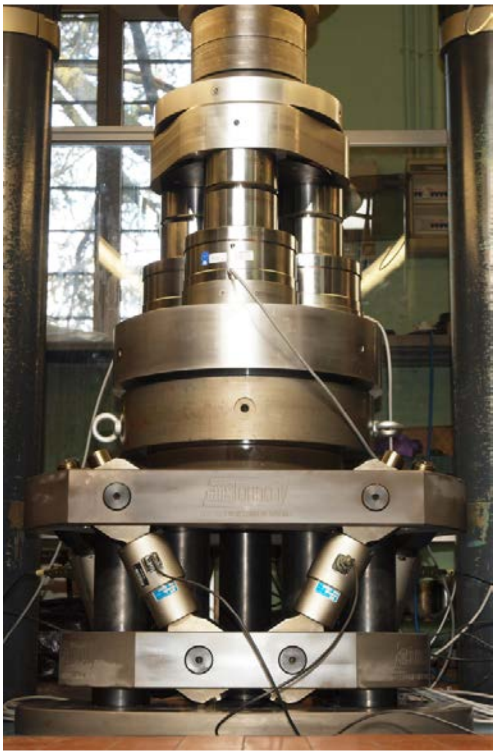

Fig. 8. 6 MN BU system mounted on the 5 MN Hexapod for a comparison

For the BU system, a software tool developed within this project [3] has been used which enables the calculation of the force introduction point. The center of the force introduction was measured, influenced by an uncertainty in the centering of the two systems and some effectuated deviations (Figure 9). The results will be used for the analysis of the new six component Hexapod.

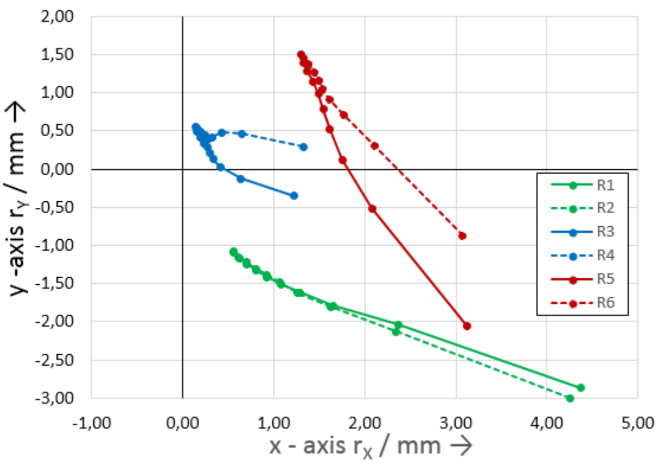

Fig. 9. Centre of force introduction during a measurement, all six series of ISO 376 are presented

The 6 MN BU system was also used to simulate a calibration of PTB´s 5 MN FSM using the 2 MN deadweight FSM as the primary standard. At first, all three single transducers were calibrated in the 2 MN FSM. The uncertainties measured within this calibration according to ISO 376 are listed in Table 3. The three transducers have very similar uncertainties, so only one transducer is listed. Table 3 also shows the result of the complete system calibration in the 5 MN FSM. It was the aim to use the same load steps in both machines for the single transducers, so no interpolation error had to be taken into account. For that reason, the highest load step used for this trial is 4950 kN (3 × 1650 kN).

Table 3. Uncertainties of the calibration of a single transducer and the combined 6 MN BU System according to ISO 376

Force / kN	w_2 (repro.)	w_3 (repeat.)	w_6 (zero)	w_8 (interp.)	$w_{5'}$ (rev.)	$w_{\text{cal. case B}}$
	single transducer calibrated up to 1650 kN					(k=2)
150	0.012%	0.001%	0.008%	0.016%	0.015%	**0.030%**
300	0.008%	0.002%	0.008%	0.000%	0.008%	**0.024%**
450	0.006%	0.002%	0.008%	0.002%	0.007%	**0.022%**
600	0.006%	0.001%	0.008%	0.000%	0.005%	**0.021%**
750	0.005%	0.001%	0.008%	0.000%	0.004%	**0.019%**
900	0.004%	0.001%	0.008%	0.000%	0.003%	**0.018%**
1050	0.004%	0.001%	0.008%	0.000%	0.001%	**0.018%**
1200	0.003%	0.001%	0.008%	0.000%	0.000%	**0.017%**
1350	0.003%	0.001%	0.008%	0.000%	0.000%	**0.017%**
1500	0.003%	0.001%	0.008%	0.000%	0.001%	**0.017%**
1650	0.003%	0.001%	0.008%	0.000%		**0.017%**
	complete BU system calibrated up to 4950 kN					
450	0.007%	0.008%	0.007%	0.015%	0.015%	**0.029%**
900	0.007%	0.001%	0.007%	0.003%	0.017%	**0.025%**
1350	0.005%	0.001%	0.007%	0.001%	0.013%	**0.022%**
1800	0.005%	0.002%	0.007%	0.006%	0.011%	**0.021%**
2250	0.004%	0.003%	0.007%	0.001%	0.008%	**0.020%**
2700	0.004%	0.002%	0.007%	0.001%	0.006%	**0.019%**
3150	0.004%	0.001%	0.007%	0.003%	0.003%	**0.019%**
3600	0.003%	0.001%	0.007%	0.002%	0.003%	**0.018%**
4050	0.004%	0.001%	0.007%	0.000%	0.001%	**0.019%**
4500	0.004%	0.001%	0.007%	0.000%	0.001%	**0.018%**
4950	0.004%	0.000%	0.007%	0.000%		**0.018%**

Now, according to the uncertainty model, the systematic deviation *b* must be determined. According to the named three cases, the first one can be chosen in this trial as the behaviour of the system can be analyzed up to full load in a machine with a very good reproducibility. For that reason, all three single transducers are calibrated in the 5 MN FSM up to 1650 kN and afterward the whole system up to 4950 kN.

The results are inserted in the template developed for the evaluation of BU system measurement data within this project [3]. The systematic deviation *b* will be calculated by the template. Table 4 presents the uncertainties for $u(x_i)$, $u(b)$ and $u_c(y)$.

The deviations between the indicated values of the 5 MN FSM and the 2 MN FSM was determined by calculating the values of the measured force at the 5 MN FSM using the measured signals of the three transducers and the polynomials from the ISO 376 calibration in the 2 MN FSM. The results are compared with the indicated values of the 5 MN FSM and named as deviation in Table 4.

These results show that $u(b)$ is very similar to the deviation between both machines. This demonstrates how low the uncertainties can become if *b* can be corrected.

Tab. 4. Uncertainties according to the first uncertainty model

Force / kN	$w(x_1)$	$w(x_2)$	$w(x_3)$	$w(b)$	$w_c(y)$	*deviation*
450	0.015%	0.014%	0.014%	-0.048%	0.054%	-0.056%
900	0.012%	0.011%	0.011%	-0.020%	0.028%	-0.026%
1350	0.011%	0.009%	0.010%	-0.010%	0.020%	-0.015%
1800	0.010%	0.009%	0.010%	-0.010%	0.020%	-0.015%
2250	0.010%	0.008%	0.009%	-0.001%	0.016%	-0.004%
2700	0.009%	0.008%	0.009%	0.004%	0.015%	0.001%
3150	0.009%	0.008%	0.008%	0.008%	0.016%	0.006%
3600	0.009%	0.007%	0.008%	0.005%	0.015%	0.004%
4050	0.009%	0.007%	0.008%	0.007%	0.016%	0.006%
4500	0.008%	0.007%	0.008%	0.007%	0.015%	0.007%
4950	0.008%	0.007%	0.008%	0.007%	0.015%	0.007%

Finally, within the last task (1.6) methods for the extrapolation of partial load characteristics of single force transducers to their nominal load will be investigated. In particular, the estimation of the associated uncertainties is part of this work. The results will primarily be used in the MN range.

For some applications, complex BU systems are too expensive to be used for the extension of the force calibration capabilities. If the required uncertainties do not need to be as low as the results of the previous tasks would in principle enable, end users can extrapolate calibration values for single force transducers.

Within the first deliverable of this task, a broad database of full load and partial calibrations of several transducers of different types has been generated to get knowledge about the technical possibilities of interpolation and extrapolation.

A template has been created which generates an ISO 376 evaluation according to the number of calibrations with different load levels for each partial calibration. Subsequently, the linear, quadratic and cubic fit function are calculated. Based on this interpolation, the following extrapolations will be performed. Up to now, 4 cases are considered:

1. Using the data of an ISO 376 calibration, an interpolation of first, second and third order is calculated. This function is used for extrapolation.
2. The second method takes into account that most transducers show a quite high nonlinear behaviour in the lowest force range. This area is cut according to its expansion of higher non-linearity. The following data is used for the calculation of an interpolation polynomial of the first, second and third order, which is then used for extrapolation.
3. In method three, an interpolation polynomial of the first, second and third order is calculated based on the calibrated force range. On top load range of that calibration, the gradient of the polynomial is determined. The hypothesis states that the characteristic curve keeps this gradient up to the nominal load.
4. The last method cuts a highly nonlinear area at lowest forces similar to method 2 and then proceeds as described in method 3.

The results of all interpolation methods are compared with the calibration up to full load, known for all transducers used for this task. It can be noted that - also in consideration of various transducer types - no method shows a principal advantage. Even the simplest case, method 1 with a polynomial of the first order, works best for some transducers. But the best method can be reliably estimated from a simulated extrapolation of a 30% up to 50% calibration and the subsequent comparison with a 50% calibration. In the task a user tool is to be made available within work package 4. It should choose the most suitable method of two sub-range calibrations to 30% and 50%. Based on the large number of measurements within this task, it is possible to use statistic methods to estimate the measurement uncertainties.

5. CONCLUSIONS

The EMRP SIB 63 project is well on its way at this halftime stage enabling calibrations in the highest range of force with uncertainties of 0.02% up to 30 MN and 0.05% up to 50 MN. A wide-ranging database has been collected, the first results and adapted investigations have been processed. In the next 18 months, the uncertainty model will be improved to compensate for the systematic error between the single transducers and the combined calibrations. In addition, a new design for BU systems will be specified according to the presented first model.

6. ACKNOWLEDGEMENT

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REFERENCES

[1] D.-I. Kang, H.-K. Song, J.-T. Lee, Establishment of large Force Standards based on built-in Force Transducers and Build-Up System, Proc. XVI IMEKO World Congress, Vienna, Austria, 25 - 28 September 2000, http://www.imeko.org/publications/wc-2000/IMEKO-WC-2000-TC3-P077.pdf

[2] Lira and Wöger, 1998, Evaluation of the uncertainty associated with a measurement result not corrected for systematic effects, Meas. Sci. Technol. 9, 1001-1011A. V. Oppenheim, R. W.

[3] Wagner, Tegtmeier, Processing and evaluation of build-up system measurement data, XXI IMEKO World Congress “Measurement in Research and Industry”
August 30 - September 4, 2015, Prague, Czech Republic

JRP website address:
http://www.ptb.de/emrp/forcemetrology.html